Multi-Channel Transcutaneous Cortical Stimulation System

Contract # N01-NS-7-2365

Progress Report #11

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The goal of this project is the design, fabrication, and testing of a ***Multi-Channel Transcutaneous Cortical Stimulation System*** to be used in a prototype artificial vision system**.** During the past 25 years, the development of a neuroprosthesis that could be used to restore visual sensory functions has been an important goal of the Neural Prosthesis Program (NPP) of the National Institute of Disorders and Stroke, National Institutes of Health. Demonstrations of the feasibility of a visual prosthesis have reached the stage in which the NPP is highly motivated to initiate the development of a fully implantable cortical stimulation system which could be used to provide inputs and computer control for hundreds, to over one thousand, implanted cortical electrodes. This is the eleventh progress report for this project. In this report we describe the details of the Closed-loop Class-E transmitter that will be used as the extracorporeal communication device that will send commands to the implanted 256-channel cortical stimulator.

The basic topology of the Class-E oscillator is shown in Figure 1, below. The combination of the series capacitor, the shunt capacitor, and the transmitter coil form a multifrequency network. The impedance vs frequency plot of the multifrequency network shows a double resonance: one a a series resonant frequency, and one at a parallel resonant frequency. Between these two frequencies can be found the Class-E frequency. At this special frequency, the loss in the switching element of the converter becomes very low. The switch, across the shunt capacitor is turned on at a strategic point in the resonant cycle for which the switch voltage, and the derivative of the switch voltage are zero. Using a current-mode closed loop control maintains operation of the converter at the precise Class-E frequency. Operation and typical waveforms of a closed-loop Class-E converter can be seen in Figure 2, below. Note that when the gate of the FET is turned on, the FET drain voltage is at the negative crest of the sinusoid. This point corresponds to the coil-current zero crossing. Since the FET is only turned on for a brief portion of the cycle, FET losses can be very low.

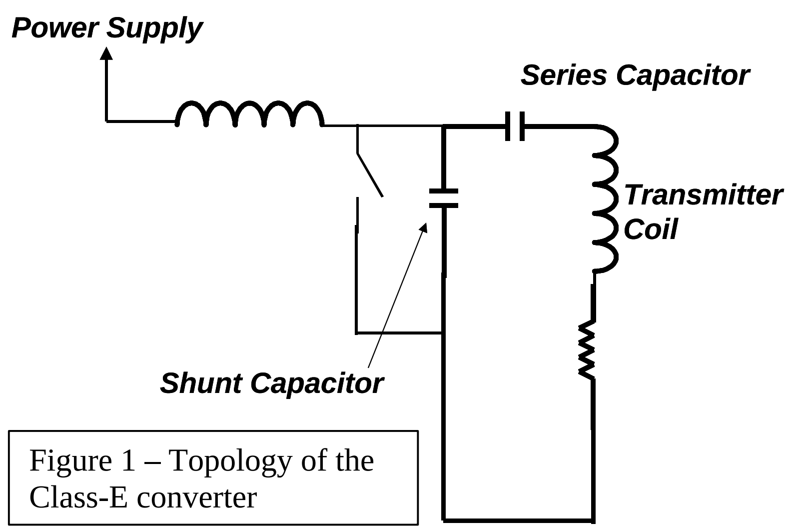

Figure 1 – Topology of the Class-E converter

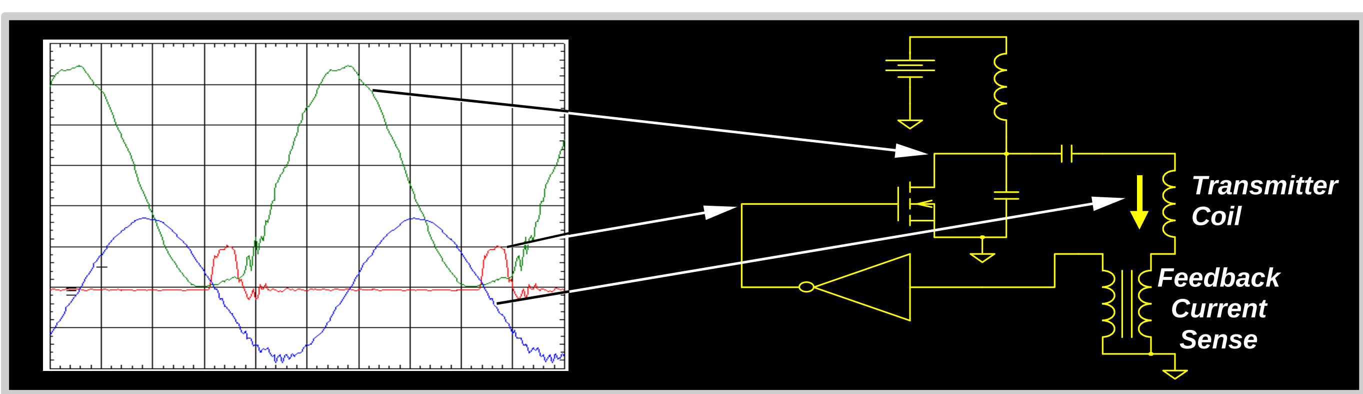

Figure 2 – Operation and typical waveforms for a closed-loop Class-E converter

Details of the design of the Class-E converter can be found in []. For this project we use a specially-designed spreadsheet that calculates the value of the shunt and series capacitor given the desired values of the coil inductance, coil Q, power supply voltage, the frequency of operation and the peak coil current. An example of this spreadsheet, for a 5MHz, 0.5 Amp, converter operating off of 12 volts is shown in Figure 3, below.

Closed Loop
Multifrequency Converter
Design Sheet

INPUT Vdc	**12**	D	f(D)	f'(D)
INPUT L in henrys	**2.00E-06**	0.2	0.118503	1.360654
INPUT I peak in amps	**0.5**	0.112907	0.024321	0.783094
INPUT f in hertz	**5.00E+06**	0.08185	0.003459	0.560178
INPUT Coil Q	**78**	0.075676	0.000137	0.515912
w = 2*pi*f	3.14159E+07	0.075411	2.51E-07	0.514015
XL = wL	6.28319E+01	0.07541	8.56E-13	0.514012
R = XL/Q	8.05537E-01	0.07541	0	0.514012
Idc = (I^2*R)/(2*Vdc)	0.010714476	0.07541	0	0.514012
C.R. = Idc/I	0.018963674	**0.07541**	0	0.514012
D	0.075410349	fseries	3949175	
Vp = (2*Vdc)/(1-D)	2.59575E+01	fparallel	5010812	
re(a)	-6.49412514	fp/fs	1.268825	
im(a)	-1.5679587	V(C2)	19.59849	
mag(Vs')	13.36146037	V(L2)	31.41593	
Zs = Vs'/I	2.36486E+01	**Output values**		
Xs = (Zs^2-R^2)^.5	2.36349E+01	**Cseries=**	8.12E-10	**farads**
C2 = 1/(w(XL-Xs))	8.12078E-10			
re(b)	0.118402325	**Cshunt=**	1.33E-09	**farads**
im(b)	-0.25312442			
Ic'	0.55889563	"ON" time	0.02	**uSec**
C1 = Ic'/(w*Vs')	1.33146E-09	DC current	0.01	**amps**

Figure 3 – Format of the spreadsheet used to design the closed-loop Class-E converters

In the spreadsheet, the values in the yellow-highlighted block are inputs. The values of the series capacitor, Cseries, and the shunt capacitor, Cshunt, are outputs. Other important parameters that the spreadsheet calculates are: the power supply current, the switch on-time, the series and parallel frequencies, and the peak coil voltages.

To modulate the transmitter, we are using the suspended-carrier method. Implementation of this technique can be seen in Figure 4, below. Note that a second switch is inserted in series with the transmitter coil. During the normal resonant cycle, the suspended-carrier switch is left closed. For this normal operation the energy moves back and forth between the shunt and series capacitors, and the coil. When all of the energy is stored on the two capacitors, and the inductor current crosses zero, the suspended carrier switch can be opened. To prevent discharge of the capacitors a diode is placed in series with the power supply and the Class-E converter switch is left open. The charge can be stored on the capacitor for an extended period of time with little to no decay. In this manner, the converter coil current can be made to change from the normal peak value to zero within a fraction of a cycle, and the converter can remain "suspended" in this state for as many equivalent cycles as desired. Oscilloscope waveforms taken from the 5MHz Class-E converter can be seen in Figure 5, below. In the top part of Figure 5 simulation waveforms from a PSpice simulation are shown. In the lower half of Figure 5 an oscilloscope photograph can be seen. Note that the converter current quickly returns pack to the level that is was at prior to the suspension of the carrier.

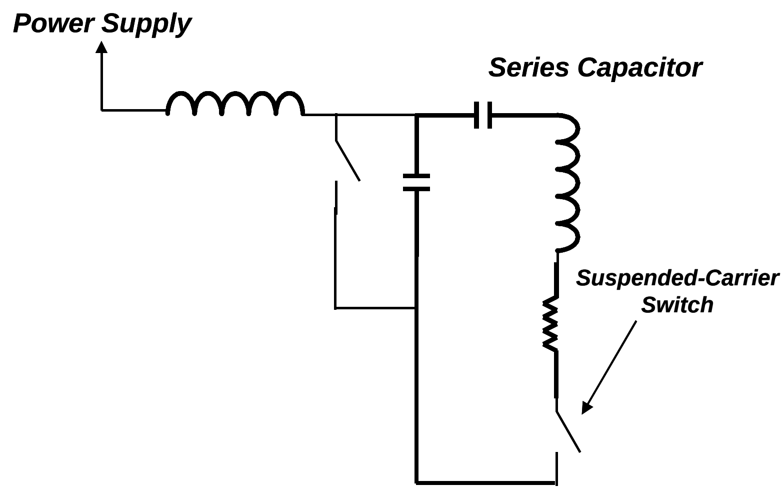

Figure 4 – Topology of the suspended-carrier method

It can also be seen, in Figure 5, that the current does not immediately cease, as theory would predict. Rather, there is a transient ring-out that occurs each time the suspended-carrier switch is opened. The cause of this can be seen in a revised model shown in Figure 6, below.

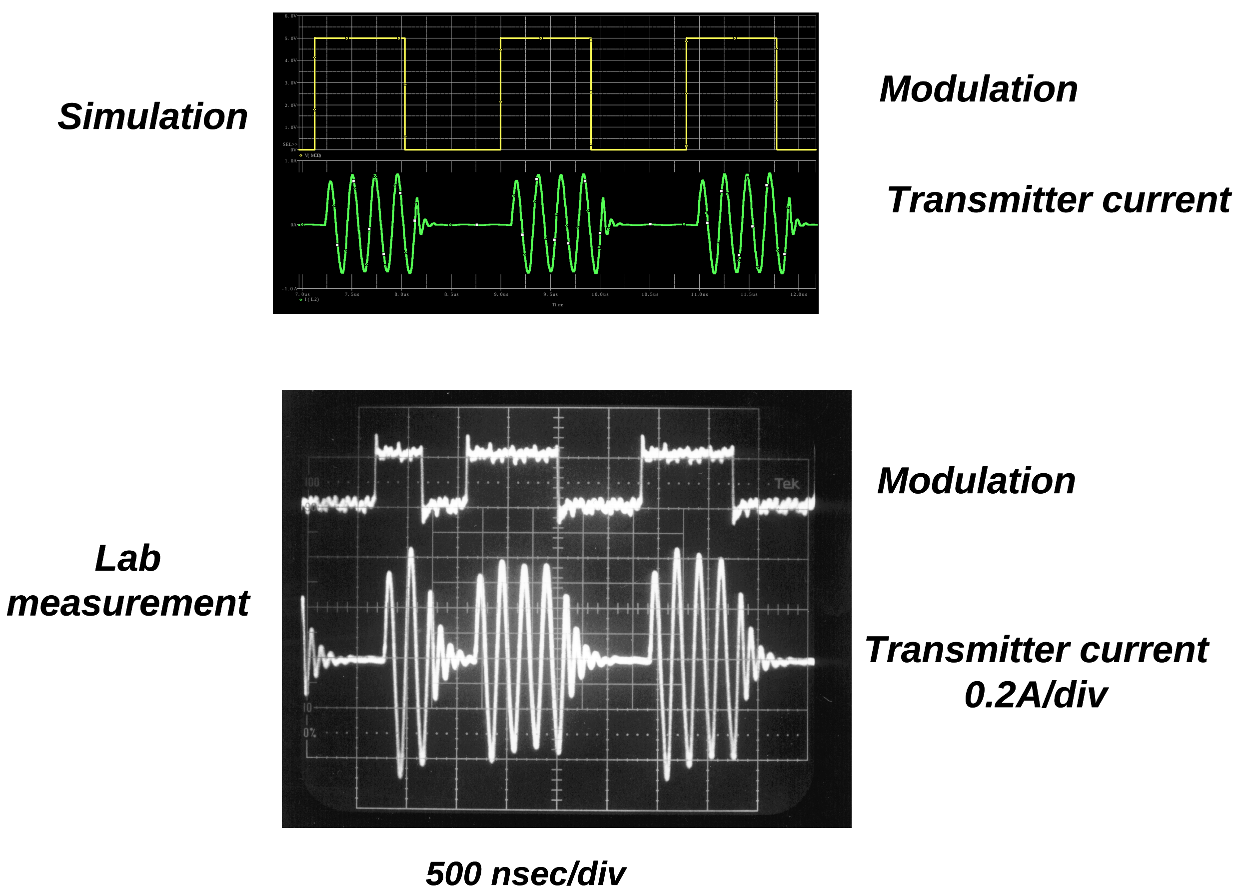

Figure 5 – Simulation and Oscilloscope waveforms for the suspended-carrier transmitter

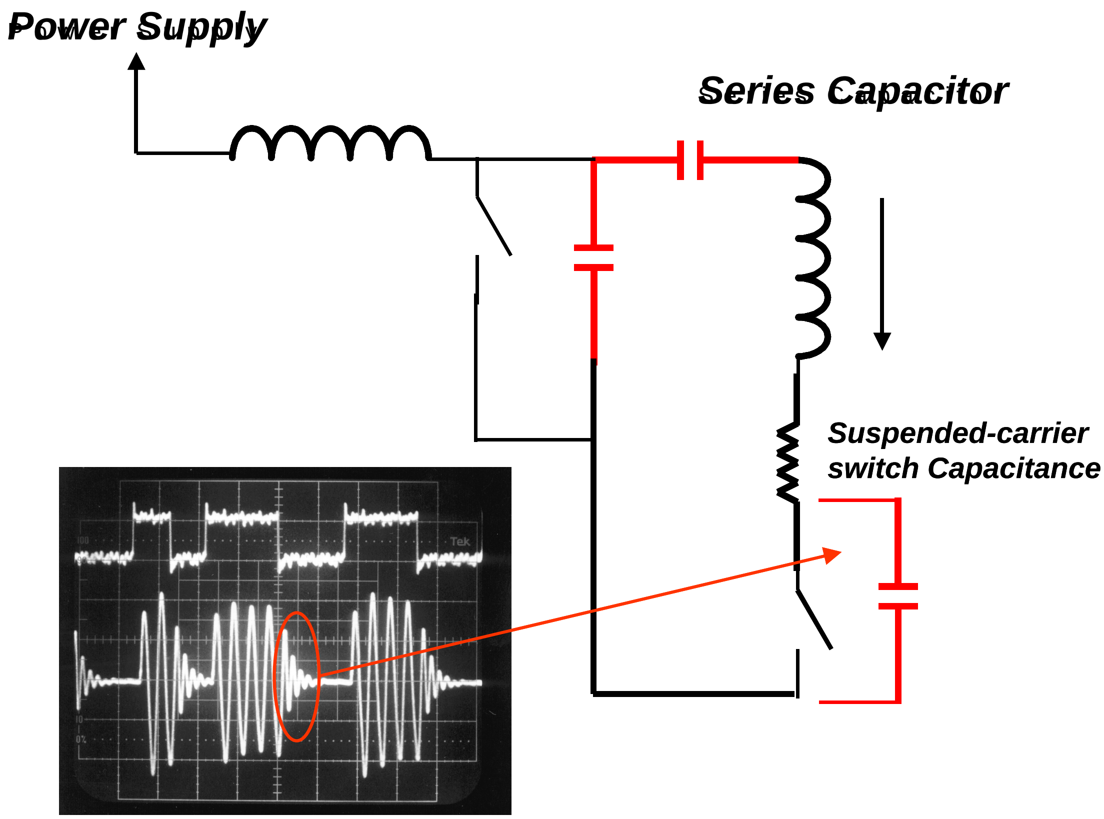

Figure 6 – Modified suspended-carrier model showing addition of the switch capacitance.

The suspended-carrier switch is not ideal. Rather it is implemented using a power FET. In order to obtain a low on-resistance, it is desirable to use a large area FET. However, a large area FET also is characterized by a large capacitance. When the switch is opened, this capacitance must be charged. For this to happen, current flows through the inductor transferring energy from the series capacitor to the suspended-carrier switch capacitor. Analysis of the circuit during the charging of this switch capacitance shows that the circuit would continue to ring at a new higher frequency determined by the value of the switch capacitance. Although not shown in Figure 6, it is necessary to use a snubber network across the suspended-carrier switch in order to cause the higher-frequency ringing to damp out. Of course some energy is lost when the switch is turned back on, while resuming normal operation. This is the cause of the first cycle of the resumed current being slightly lower than the steady state peak current value.

The energy lost during the charging and discharging of the suspended-carrier switch can be minimized by choosing an FET with a capacitance that is significantly lower than that of the series capacitor. However, high-voltage, low-resistance, FETS are also characterized by high-capacitances, thus resulting in a design compromise. This is a fundamental limitation of the suspended-carrier method.

During the next quarter we plan to use this 5MHz Class-E transmitter, modulated by a computer to test the operation of our first-generation front-end decoder ASIC.